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ABSTRACT

Design tradeoffs for a clay repository were evaluated using the Disposal Systems Evaluation Framework (DSEF) being developed at Lawrence Livermore National Laboratory. The goal of the design tradeoff study is to identify repository design options that enable use of large waste packages. Concepts evaluated include those with pre-closure ventilation (open mode) as well as those with backfill installed at the time of waste emplacement (enclosed mode). Open mode systems maintain an air gap between the waste package and the rock (drift or borehole) wall, across which the primary mode of heat transfer is thermal radiation. In enclosed mode systems, there are multiple layers of the Engineered Barrier System (EBS) between the waste package and the rock wall, such as buffer, envelope, backfill, and a liner.

DSEF includes user-friendly options to facilitate the documentation of conceptual repository design alternatives for a wide assortment of waste forms, geologic environments, and repository dimensions and operating modes. DSEF allows the user to gather and utilize EBS design variables that are tailored to a specific repository design. DSEF also maintains a case library of hundreds of predefined cases of executed thermal analyses and draws input from databases of material properties and repository development cost data. Design tradeoff studies use the DSEF Excel 2010 component to prepare input data to the MathCAD-15^{TM} component of DSEF (which applies an analytical thermal model solution to evaluate design alternatives).

Open mode systems use preclosure ventilation to remove most of the waste heat during the time that thermal output is high and benefit from efficient thermal radiation heat transfer from the waste package to the rock until backfill is installed. In contrast, enclosed modes with immediate backfill emplacement must transfer all of the waste heat through conduction in materials with relatively high thermal resistance. The result is that open mode repository designs can emplace larger waste packages with high heat loads after less surface storage time than enclosed modes in the same geologic medium.

The current design tradeoff study finds combinations of closure time and waste package capacity that meet a specified thermal constraint. The locus of these points is a design curve with the space on one side of the curve having design margin. A family of design curves can be developed as other parameters are varied, including emplacement mode, spacing of waste packages and drifts/boreholes, ventilation efficiency and duration, and thermal constraint. Ultimately, the repository design tradeoffs quantified by these families of curves are themselves inputs to the larger cost/performance tradeoffs to specify the configuration of the overall waste management system, including consolidated interim storage and repackaging.

INTRODUCTION

Two other papers presented at the 2013 IHLRWM conference present the background and a description of the structure and information flow of DSEF [1] and the potential repository design solutions for disposal of large waste packages resulting from the parametric studies performed using the Mathcad thermal analytical component of DSEF [2].

This paper presents the results of a series of parametric sensitivity studies developed over a two-year period in [3], [4], and [5], and utilized in [6] and [7].

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The primary purpose of DSEF is to help the user tackle a multi-dimensional set of alternatives and options to arrive at workable high-level radioactive waste repository concepts.

For each combination of surface storage time, fuel cycle, and geologic medium, there are multiple Engineered Barrier System (EBS) design concept options for (1) Waste package spacing; (2) Waste package capacity; (3) Drift / borehole spacing; and (4) EBS components, radii, and material properties.

There are many options to deal with and much input data for all of the analysis cases. DSEF helps the user take advantage of previous analyses to define potential new configurations and analysis cases that can meet the design and operating constraints.

Open and Enclosed Repository Design Concepts

The FY11 disposal concepts report, *Generic Repository Design Concepts and Thermal Analysis (FY11)* [6], recognized open and enclosed emplacement modes and recommended further work to evaluate one or more open modes. Enclosed modes were defined to include disposal concepts that call for waste packages to be in direct contact with any surrounding solid medium such as buffer material, backfill, or host geology. For enclosed modes, the direct contact begins immediately at emplacement or shortly thereafter, with that contact influencing peak near-field temperature. Open modes maintain unsaturated, air-filled open spaces around the waste packages for some time prior to permanent closure, and even after closure for some concepts.

Open mode concepts were evaluated in [5] and [7], and are discussed further in this conference in [2]. Reference [3] evaluated a set of base case open mode repository design concepts and developed a number of parametric sensitivity studies for the open mode repository concepts.

Base Cases and Parametric Studies Evaluated

The base case analyses in Reference [3] included:

1. Commercial LWR UOX spent nuclear fuel, with burn-up values of 40 GWd/MT and 60 GWd/MT
2. Waste package sizes of 4, 12, 21, and 32 PWR (4P, 12P, 21P and 32P) assemblies
3. Surface storage times of 50 and 100 years
4. Ventilation system operating times of 250 years for SNF with 50 years of surface storage, and 200 years for 100 years of surface storage time (i.e., 300 years between removal from the reactor and start of closure operations)
5. A constant ventilation thermal efficiency of 75%
6. Backfill installation completed 10 years after termination of the ventilation system operation, with a mixture of 30% quartz sand and 70% bentonite

Parametric sensitivity studies were performed in Reference [3] as one-off studies from the base cases, including:

1. Ventilation efficiencies of 50, 60, 70, 80, and 90%, in addition to the base case of 75%
2. Ventilation system operating times of 50, 100, 150, and 200 years, in addition to the base case of 250 years (in combination with 50 years of surface storage)
3. Drift/borehole spacing variations of 40, 50, 60, and 70 m, in addition to the base case of 30 m
4. An assumed generic rock type with host rock thermal conductivities of 1, 2, 3, 4, and 5 W/m-K, and associated thermal diffusivities assuming a constant volumetric heat capacity typical of clay
5. An assumed generic engineered backfill with thermal conductivity values of 1, 2, 3, 4, and 5 W/m-K. The higher values in this range are achievable using a mix of bentonite, sand, and graphite [8] and [9].
6. An uncertainty analysis for clay and alluvium designs, assuming the mean values of volumetric heat capacity, and with thermal conductivity plus or minus one or two standard deviations.

The Reference [3] base case thermal response for drift/borehole rock wall and waste package surface temperatures in a clay/shale environment are shown in Figure 1. Peak temperatures increase linearly with waste package capacity. The influence of burnup is shown by the separation between the pairs of curves, while the minor influence of surface storage time is shown by the close spacing of the curves.

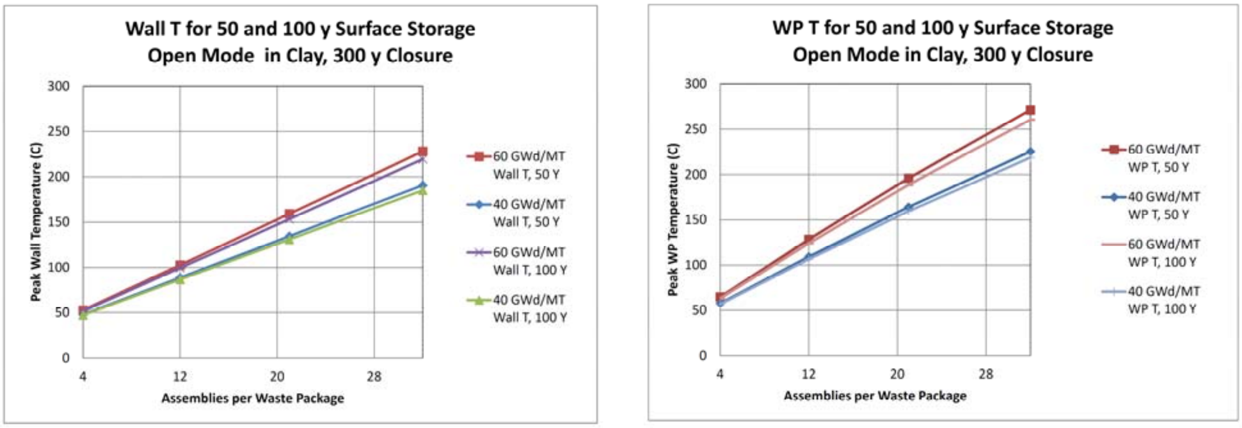


Figure 1 – Base case peak rock wall and WP temperatures in open-mode clay for two burn-ups and two storage times (10 m waste package spacing, and 30 m drift spacing)

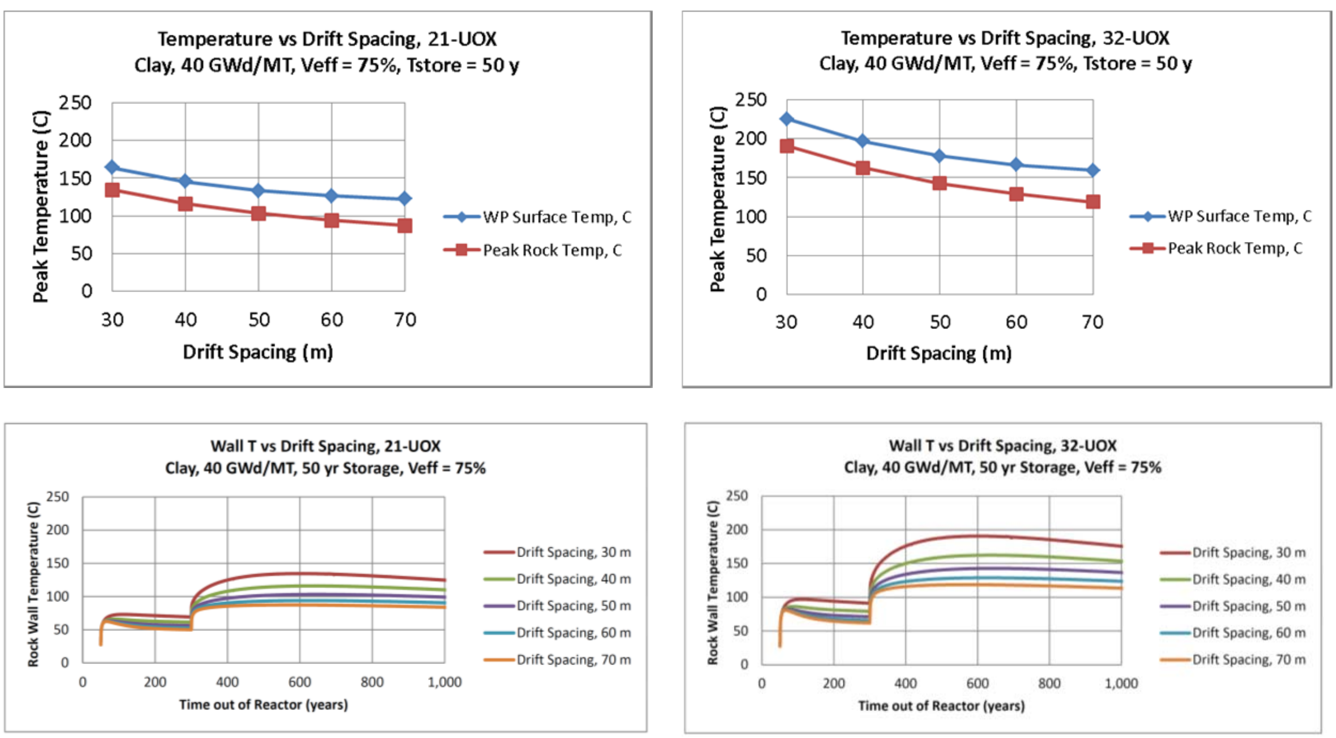


Figure 2 Effect of drift spacing on peak rock wall and WP temperatures in open mode clay for 21P and 32P WPs with burn-up of 40 GWd/MT, ventilation efficiency of 75%, and surface storage time of 50 years. The 250-year ventilation period ends at 300 years out of reactor

Figure 2 shows the Reference [3] results of parametric sensitivity analyses for drift spacing ranging from 30 to 70 m for 21 and 32-assembly waste package sizes. The top two panels show that increasing drift spacing results in lower peak temperatures, but with diminishing changes for large drift spacing. The lower two panels show the rapid temperature rise when ventilation ceases.

THERMAL CONSTRAINTS

Waste package size and repository layout configurations are generally limited by thermal constraints imposed on the near field environment. An example of thermal constraints for enclosed mode designs are those considered to limit alteration of clay in buffers, by illitization or cementation. Alteration generally involves dissolution, aqueous transport, and precipitation. Alteration products can include illite (for temperature >150°C in the presence of potassium ions), and silica (as a precipitate). Clay alteration generally degrades swelling pressure, increases rigidity (promoting fracture), and potentially decreases sorption.

In the enclosed mode repository design concepts [3 and 4], the thermal constraints in the various geologic media were primarily derived from the Engineered Barrier System (EBS) material constraints associated with bentonite buffer materials in clay and granite repository environments (100°C), and with the salt backfill adjacent to the waste package (200°C) in the bedded salt environment.

The open mode design concepts evaluated in [5] assume a bare waste package, with or without placement of backfill at closure in clay/shale and alluvium host rock designs. The goal of the open mode analyses was to keep the peak temperature of the natural barriers (the host rock wall) less than or equal to temperature constraint values for the host rock clay of 100°C, 120°C, and 140°C. The lower value is conservative, and higher values would require considerably more testing and would entail a more difficult licensing case.

In practice, for large waste packages and short ventilation periods, it might be possible to keep a portion of the engineered barrier of the backfill material below the temperature constraints, if the peak wall temperature is lowered to create some margin (e.g., by increased drift spacing), and if the engineered backfill thermal conductivity is increased sufficiently by addition of sand and/or graphite to bentonite.

In open mode concepts, one can consider moving the temperature constraint a small distance into the host rock, allowing a relatively thin "sacrificial" layer of host rock immediately adjacent to the emplacement drift to exceed the thermal constraints. This would only be acceptable if the performance assessment analyses had sufficient margin in the remaining engineered and natural barriers.

ANALYSIS OF REQUIRED VENTILATION TIME TO MEET THERMAL CONSTRAINTS

In the present work, an iterative approach was used to converge on open mode ventilation (and closure) times required to meet the three alternative thermal constraints. A version of the DSEF Mathcad tool was developed that iterates one independent variable (ventilation duration in this study) until the specified thermal constraint (peak clay rock wall temperature of 100, 120, or 140°C) is met, for constant rock wall radius (2.25 m), storage time (50 or 100 yr), backfill thermal conductivity (1.2 W/m.K installed at closure), and drift spacing (30, 45, or 60 m).

Figure 3 shows design curves for 12P, 21P, and 32P waste packages, all with burn-up of 40 GWd/MT, and all with 10 m (center to center) between waste packages. The ordinate on each set of design curves is the shortest ventilation duration after emplacement for which the rock wall does not exceed the specified thermal constraint. The abscissa on each set of design curves spans drift spacing between 30 and 60 m. Space above and to the right of each curve (higher ventilation time and/or wider drift spacing), results in design margin between the temperature constraint and the predicted peak temperature. The solid curves span thermal constraints of 100°C (green), 120°C (blue), and 140°C (red). For a given thermal constraint (curve color), the line style covers storage time (between removal from the operating reactor and emplacement in the ventilated repository) of 50 yr (solid curves) and 100 yr (dashed curves).

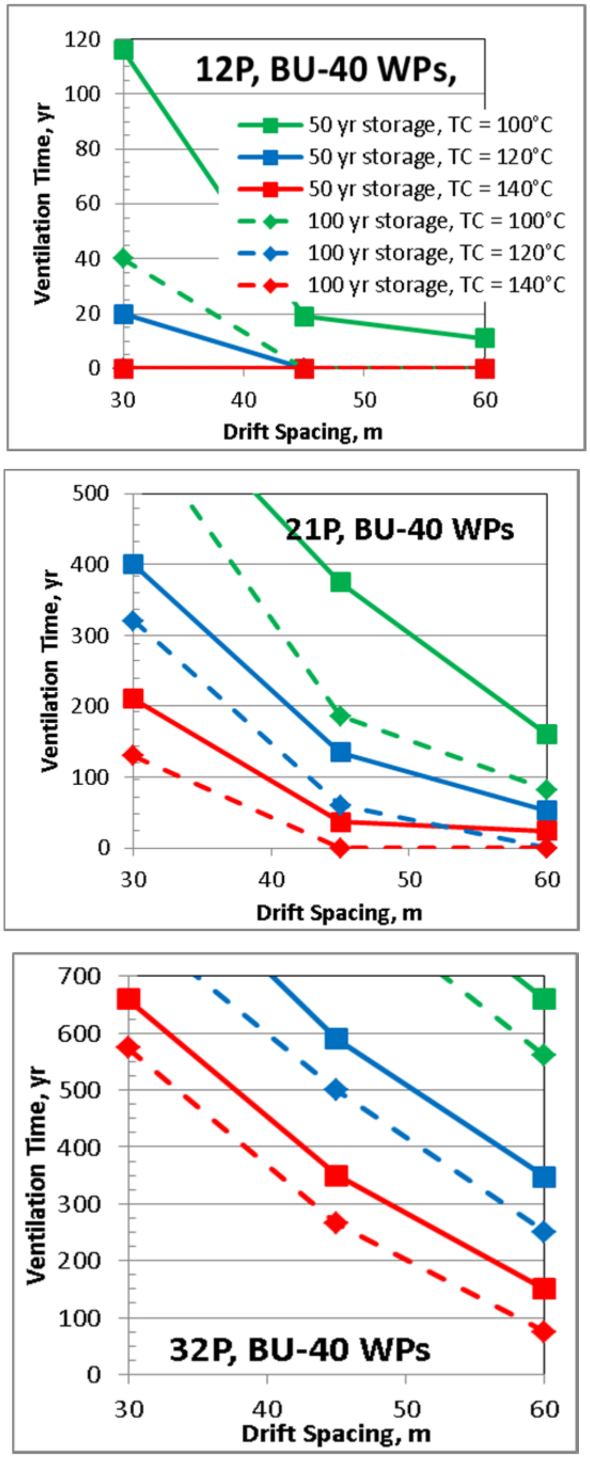


Figure 3 – Design curves for required ventilation time versus temperature criteria and drift spacing, with 10 m waste package spacing

Inspection of Figure 3 shows that required ventilation time is more sensitive to drift spacing and temperature constraint than to pre-emplacement storage time (e.g., for 32P, ventilation time decreases by 445 yr as drift spacing doubles, and decreases by 485 yr as temperature constraint increases by 40°C; both for 50 yr of surface storage; while ventilation time decreases by only 100 yr when storage time is doubled). This is as expected because ventilation can conservatively remove 75% of the waste heat [10], making it nearly as effective as surface storage.

The intent of the design curve study was to identify designs for a clay repository that could accommodate large waste packages. The first step in attaining that goal was to change from the enclosed mode to the open mode of repository design, to take advantage of both ventilation and efficient thermal radiation heat transport. This moves the temperature constraint location to the rock wall, which is significantly cooler than the waste package surface. This open mode design can be backfilled at closure for mechanical stability, but does not include a hydrologic bentonite EBS component. It should be noted that moving the temperature constraint a meter or two into the rock wall can provide further benefit for large WPs, if a “sacrificial layer” is acceptable in the overall performance assessment.

For 12P WPs with nominal burn-up of 40 GWd/MT, even the most conservative temperature constraint and short surface storage time produce required ventilation times much less than 200 years. These are significantly larger waste packages than in enclosed mode clay repository designs, because the temperature constraint is not directly next to the waste package surface. For 21P waste packages (the size and approximate burn-up of those designed for Yucca Mountain), 60 m drift spacing is adequate for all the combinations of surface storage time and temperature constraint considered, with most combinations also working at 45 m drift spacing, and with the 140°C temperature constraint working at 30 m drift spacing. For 32P waste packages, 200 yr of ventilation time can meet a 140°C temperature constraint for 60 m drift spacing.

There is another design variable that can also be used to reduce the required ventilation time; that variable is the axial spacing between waste packages.

Table 1 shows the fraction of the rock-wall peak-temperature rise above ambient that is attributable to the central WP, the axial neighbors (separated by the waste package spacing), and the lateral neighbors (separated by the drift spacing), for three of the 54 cases shown in Figure 3 that require well more than 200 yr of ventilation. The contributions from the axial neighbor waste packages (affected by WP spacing) are large in each case. Increasing the waste package spacing to 20 m results in reduced axial neighbor contributions to peak temperature and ventilation times of well less than 100 yr.

Figure 4 shows 18 cases with 50 yr storage time, 21P or 32P WPs, and temperature constraints of 100 and 140°C, in the four 3D plots. Figure 5 shows all 36 cases for 21P and 32P WPs with 50 yr of storage time. Even for large 32P WPs and a low 100°C temperature constraint, the required ventilation time is 145 yr, well under the 200 yr target for this study.

Table 1. Contribution to peak temperature for three cases storage time of 50 yr with very long required ventilation times. The first three rows define the three cases.

WP Size	21P	32P	32P
T Constraint, °C	120	140	120
Drift Spacing, m	30	45	60
10 m Waste Package Spacing			
Ventilation Time, yr	400	350	347
Central WP Contribution, %	15.6	19.6	24.0
WP Spacing Contribution, %	68.8	60.5	51.5
Drift Spacing Contribution, %	15.7	19.9	24.4
20 m Waste Package Spacing			
Ventilation Time, yr	30	40	62

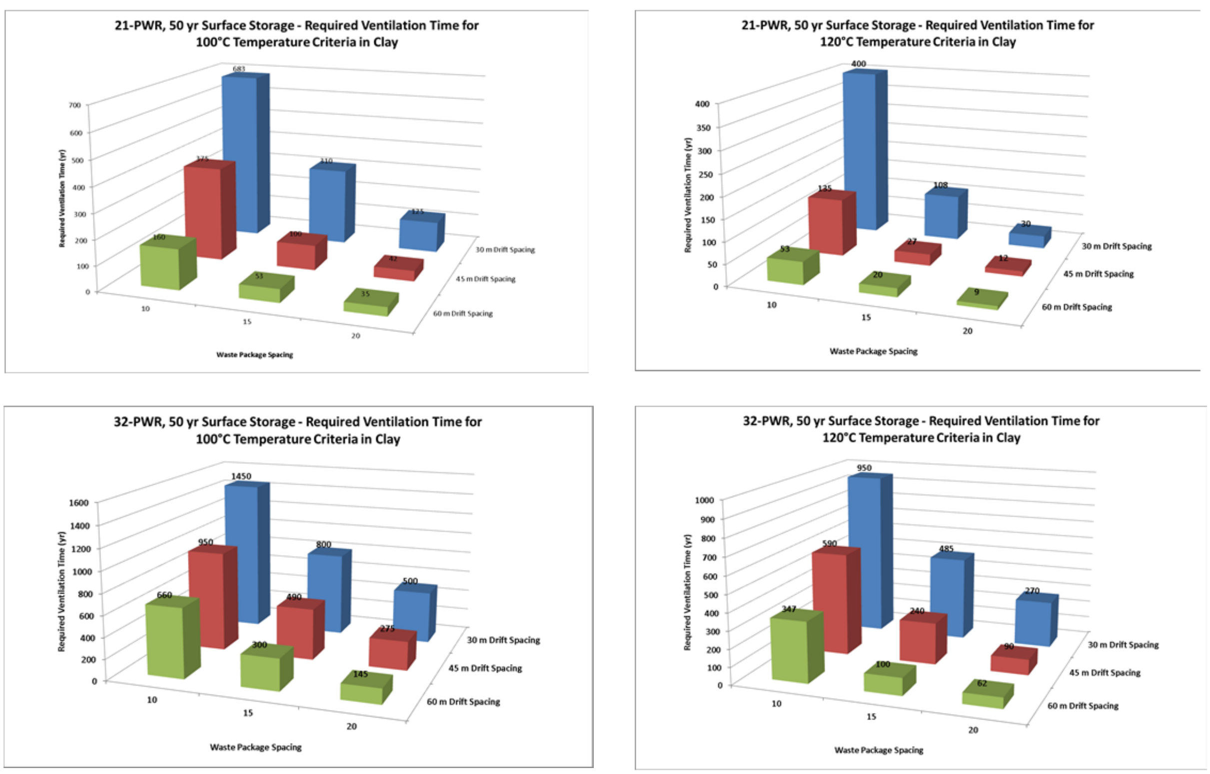
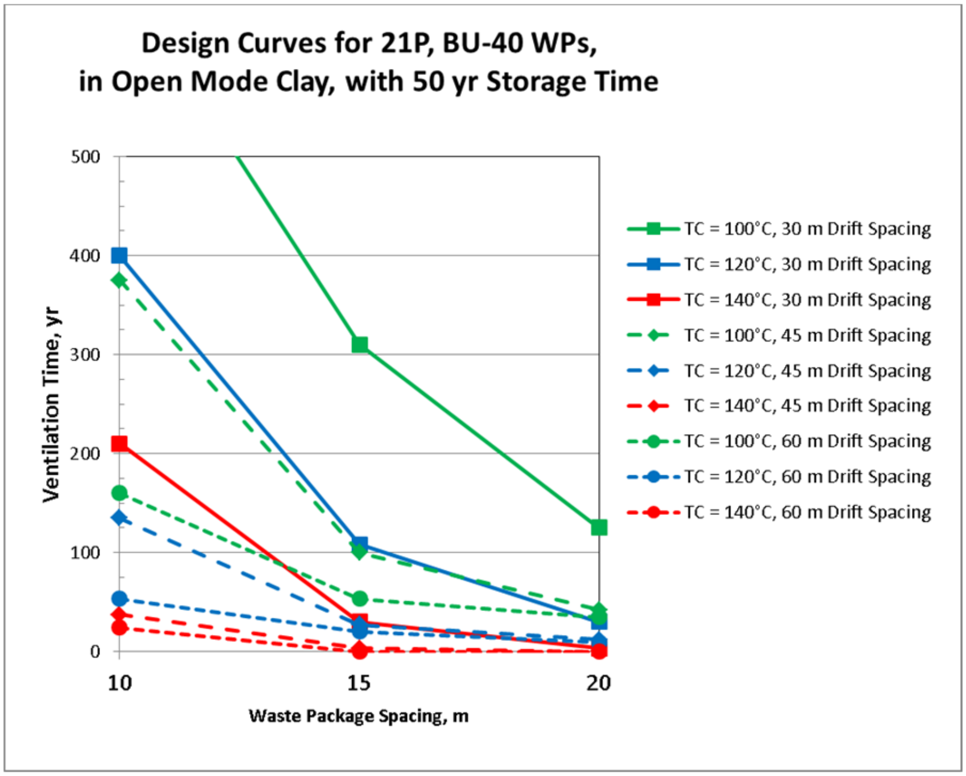


Figure 4 –Required ventilation time for 21-PWR and 32-PWR waste packages as a function of drift spacing and waste package spacing, for 50 yr of surface storage



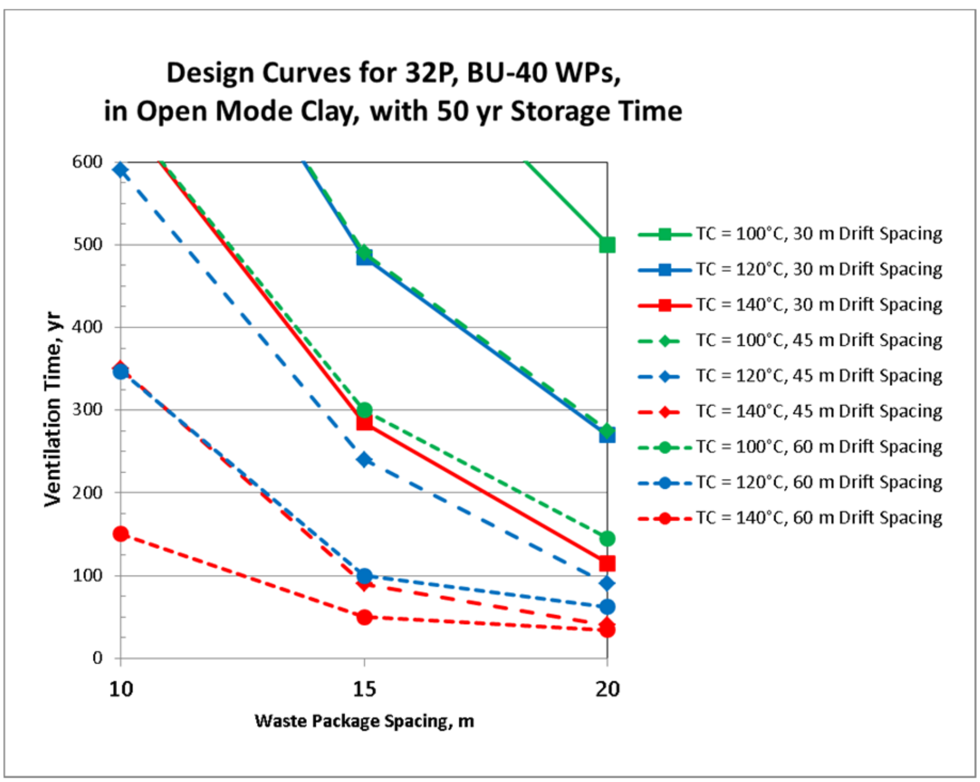


Figure 5 –Required ventilation time for 21P and 32P waste packages as a function of drift spacing and waste package spacing, for 50 yr of surface storage and temperature constraints of 100, 120, and 140°C

CONCLUSIONS

DSEF was initially developed to support analysis efforts in 2011, and was updated in 2012 [5]. More than 300 analysis cases of potential repository design and operating concepts are documented in the DSEF case library sheet and in References [3], [4], and [5].

The Mathcad analytical model component of DSEF has facilitated trade studies of alternate repository design and operating concepts, and has allowed the development of feasible repository design concepts to accommodate large waste packages.

The DSEF model was applied for a design study with objectives of emplacement of large waste packages in clay, potentially to eliminate the need to repackage the waste at the repository. The study showed the design curve approach (using data from the iterative version of the Mathcad model component), was able to perform trade studies using five independent variables (WP size, waste package spacing, drift spacing, surface storage time, and rock wall temperature constraint). For each combination of the independent variables, the required ventilation time was calculated as the dependent variable.

The results show that emplacement of large 32P WPs in clay is feasible if a 100°C temperature constraint is imposed at the rock wall, and if either a century or two of ventilation is acceptable, or the waste packages are widely spaced. For 21P and 32P designs with 20 m waste package spacing and 60 m drift spacing, required ventilation times are less than a century, and repository footprints are 11 and 17 km^2 respectively for 140,000 MTU, comparable to the 7 km^2 for a repository in unsaturated tuff.

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